TOWARDS DESIGN-TIME AND RUNTIME ADAPTABILITY

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Abstract: *There is a strong need for products that can adapt themselves to new environments, new states, and/or new user defined tasks. A literature survey on adaptable products and design shows that there are various definitions of 'adaptability'. Generally, the goal of adaptability is to extend the utility of a product and its design. Depending on the time the utility extension takes place, three types of adaptability can be recognized: design-time, runtime, and lifetime. This paper focuses on the first two types of adaptability. It deals with the design choices (e.g., design of product architecture) that should be made to obtain an adaptable product. It also describes the ways to deal with tradeoffs that have to be made in the design- and runtime.*

1. INTRODUCTION

Technical products have to fulfill a great variety of customer needs and demands in order to become competitive. Besides that, customer requirements may change many times during product life cycle. As a consequence, companies have to define adequate strategies to handle new challenges, instead of rely on their past successes. They also need to be continually innovative to survive in the current market [1,2]. Adaptability (or: flexibility) has been suggested as a useful 'instrument' to remain competitive, since it enables companies to quickly react on changing customer demands as well as on technology evolution [3].

Most of the current development approaches specify functionality of products during design time. This results in products that function well only within a well-defined range of conditions (e.g., constant temperature of the environment). To be able to easily adapt or modify products to various environmental and working conditions, it is necessary to use adequate development approaches.

In the literature, no standard design methodology to design adaptable products can be found. There are, however, few rules, generalized methods, software tools, and guidelines for designing such products. In software and mechanical design, several methods for increasing adaptability are available [4-10]. None of those methods, however, can be considered as superlative for design for adaptability, since all of them have been proposed taking different definitions of adaptability into account. The kind of adaptability, however, strongly determines design for adaptability. Beside adaptable production technologies and processes, adaptability includes development of adaptable products.

Designing an adaptable product is not trivial; many aspects need to be changed or adjusted during the design process in order to obtain an adaptable product. This can include a change of product parameters (e.g., from constant values into variables) as well as a change (or modification) of the product architecture. For runtime adaptable products, appropriate action plans have to be determined in order to plan the adaptability. Moreover, the control of the product can change, and the software will need to be adjusted.

This paper focuses on aspects that should be taken into consideration during designing an adaptable product. In the following sections of the paper, we describe and classify adaptability. We also present our concept of adaptable product, design choices that should be made to obtain such product, and a way to deal with tradeoffs that need to be made.

2. ADAPTABILITY

The goal of the adaptable product is to extend the utility of the product and its design. Extension of the utility can be done at different moments: during design – design-time adaptability, when product performs a task – runtime adaptability, and by prolonging product's service life in its normal operational mode by adapting it to new operational modes – lifetime adaptability. Adaptability of the product design is of importance to the producer. The design-time adaptability is related to reuse of the existing design in order to produce products that response to exogenous changes (e.g., customer needs) or endogenous changes (e.g., better solution approach) [3]. In case that a product has a specific design that cannot be modified to produce new products, term 'design-time adaptability' is irrelevant.

In the literature, different terms are used to describe adaptability: flexibility, changeability, versatility, adaptability. All those terms describe comparable, but slightly different aspects of product development process and properties of technical products [6-13]. In this paper, we define adaptability as product's parameters (characteristics) that can be changed (adapted) to improve performance of the product in predictable situations. The parameters can be changed real-time (active) or when the product is not in use (passive). The parameters can be changed only by the product self and not by the user.

3. ADAPTABLE PRODUCT

As said in the Introduction, designing an adaptable product is not trivial. Especially, when products are complex. An example of a complex product is a mechatronics product, which incorporates knowledge of different engineering disciplines (e.g., electronics, mechanics, computer science). Designing an adaptable complex product remains a challenge. Especially, when no standard theoretical framework to design such a product exists. In order to formalize a design method, we introduce a general idea of an adaptable product. Figure 1 shows a scheme of an adaptable product. The scheme presented in that figure has been derived based on the well-established philosophy behind control engineering. The scheme gives an overview on seven general aspects of the adaptable product. Definitions of each aspects (presented as a components in the scheme) are given in the following sections.

3.1. Tasks

Tasks represent input for the control and decision system of a product. In general, tasks are defined as user demands. An example of two different tasks for a printer can be a double-side full-color printing, and one-side monochrome text print. In both cases, behaviors of the printer are different.

3.2. States

States, similarly to tasks, present input for the control and decision system of a product. The difference between the tasks and states is that states are not directly introduced by the user, but they are measured by the product itself. The states give information about the system itself and the environment. In case of a car, an example of the state can be a temperature inside a car, or the amount of petrol left. An important information, which is also included in the states is aging and deterioration of the product (e.g., state of the components), and pattern of usage (e.g., frequency of use).

3.3. Control and decision system

The control and decision system of the adaptable product is responsible for recognizing changes in the input information. Based on the recognized change, the control and decision system determines an action that has to be performed by the product. This requires appropriate 'action plans' for the product in order to execute adequate operations against changing conditions. To maintain a high-quality output, it is necessary to have an action plan for the real-time controllers.

3.4. Adaptability instruments

Based on the input information, an adaptable product should adapt to changing conditions. This is done using 'adaptability instruments'. In contrast to control and decision system, adaptability instruments are passive. They can be defined as a list of all possible instruments that are available for the control and decision system in order to adapt the product. The list can include simple parameters (e.g., speed, temperature) as well as more complex actions (e.g., reconfiguration of the system). Adaptability instruments are, therefore, defined as everything that can be modified using the control and decision system in order to adapt the product to changed working conditions. The choice of adaptability parameters determine to what degree the product can be modified.

3.5. Functional part of the product

The part of the device that actually executes the work that has to be done is called functional part of the device. In case of a printer, the functional part of the device is the part of the printer that makes an image (or text) on the paper, and any mechanism that support that function.

3.6. Feedbacks

All the sensory information about the output of the product are defined as feedbacks. Feedback is an input for the control and decision system. In case of a copy machine, an example of the feedback is a quality (e.g., contrast) of the copy measured by the copy machine self. User input about quality of the copy is not considered as feedback, but rather as a task.

To be able to use feedbacks in adaptable products, it is necessary to define measures of the output. Those measures will be specific for the product, designer, and the company. Most of the present products do not contain feedback. It is, however, useful to include feedback in the product, since it gives valuable information about the quality of work performed by the product. This information together with the states and tasks gives better overview for the control and decision system. It will, therefore, be useful when (re)designing an adaptable product.

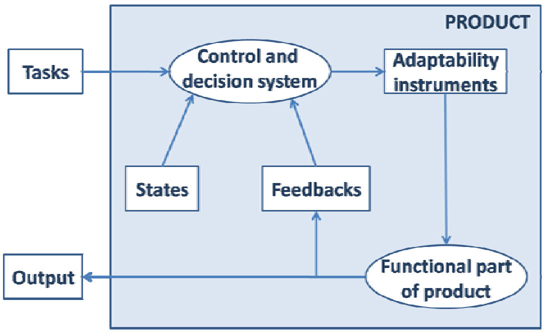

Fig.1. *Schematic representation of an adaptable product.*

4. DESIGN CHOICES

In most of the cases, market requirements define the tasks and the output of the product. In consequence, the tasks and the outputs do not offer a lot of freedom to the designer. Except for the tasks and output blocks, all the blocks included in the scheme in Fig. 1 are design choices. The design choices include:

- methods that should be implemented in order to control the system and to decide on actions that should be taken in order to make product adaptable
- input information that is needed for the product in order to make it adaptable
- adaptability instruments that should response to the input information.

The first point refers to the control and decision system, while the two other points refer to product architecture.

4.1. Design of control and decision system

During designing of an adaptable product, the designer should foresee possible environmental changes as well as changes in working conditions of the product. Based on that, action plans for the product can be derived. Action plan can be defined as a list of all the tasks (actions) that have to be carried out in order to achieve and objective. Action plans for the adaptable product are necessary to make a reorganization or reconfiguration operations against changing conditions of the product. Those changing conditions include changes of tasks, aging, deterioration, and environmental changes.

Decision on *which* adaptability instruments should be used in adaptation of the product is made using control and decision system. The control and decision system is also used to decide on *how* the adaptability instruments should be adapt according to action plan derived for the specific change. Note that each adaptability instrument can be used alone or in combination with other adaptability instruments in various action plans.

When designing a product, it is necessary to make tradeoffs. A tradeoff refers to a situation, in which one objective (e.g., quality) must be decreased in order to increase another objective (e.g., number of product's outputs per hour). This implies a decision that has to be made with full comprehension of both advantages and disadvantages of a particular choice.

It has not yet been investigated how the tradeoffs should be made in case of adaptable products. Review of the literature show that Pareto efficiency (or: Pareto optimality) can be used as a formal framework for tradeoff studies between desirable product attributes [14-16].

Pareto frontier yields to provide potentially optimal solutions (Fig. 2). For that reason, finding Pareto frontiers seems to be useful when dealing with adaptable products. Pareto frontier allows designers to focus on tradeoffs within restricted set of parameters rather than considering the full range of parameters. Figure 2 shows an imaginary example of a design space with two design variables x and y (Fig. 2a) and a performance space with two objective functions F1 and F2 (Fig. 2b).

In case of adaptable products, design variables can be called adaptability instruments, and the objective functions – scores. Adaptability instruments presented in Fig. 2 are continuous design variables that have both upper and lower boundaries. To obtain an optimal performance of the product, minimization of scores (F1 and F2) is necessary. When designing an adaptable product, the aim will be to move between different scores along the Pareto frontier. The process of changing from one Pareto frontier point to another is not instantaneous. This is caused by the fact that the manner in which product changes directly implicates performance and time required to complete each modification. It appears that selected path for changing configurations becomes inherently important [17]. As reported by Ferguson et al., a straight vector between the two Pareto frontier points does not indicate the best manner to adapt the product [17]. In contrast, it gives possibility of violating the product constraint or loosing stability of the system.

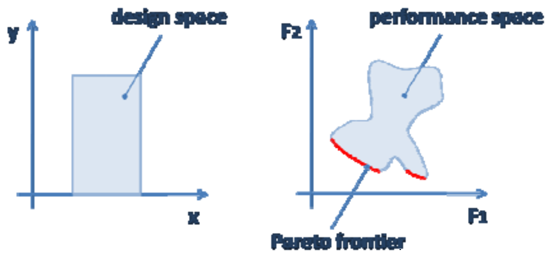

Fig.2. *Mapping from design space (left) to performance space (right) and representation of Pareto frontier.*

4.2. Design of product architecture

In order for the product to be adaptable, it has to have an adaptable architecture. Product architecture is described by architectural rules that portray the way technology elements are integrated in the product and the way these elements interfere with each other.

In view of the product architecture, adaptability can be described as questions of *where* (in which domain and at which level), *how* (which strategy), and *against what* (e.g., environment changes, aging) the reorganization and reconfiguration of the mechanical structure, states, and functional behaviors of the product takes place. In the architecture of a product, there are always tradeoffs that have to be made. Since complex (e.g., mechatronics) adaptable products are difficult to manage, modular architectures (to some extent) can help designers to design and comprehend the product.

5. MODULARITY

There are various product configuration design approaches described in the literature. The most common ones are: modular design, and product family and platform design. The concept of modularity is widely used to deal with complex (e.g., mechatronics) products, since it can be used to divide product's design process over multiple engineers [18].

When designing a modular product, a designer should minimize the interactions between components that are not in the same module. When connections are contained in one module only, component outside that module do not need any information about connections and parameters of the components of the module. Information, therefore, can be hidden into that particular module. In reality, however, there are often some connections that have to be managed, but they are not included in a module. Those connections represent interfaces between different modules and, therefore, they should be carefully defined. Only then the modules will be able to function together.

There are various methods to design a modular product [19]. One of them is design structure matrix (DSM).

6. DSM

The DSM can be used as a tool for structuring and clustering product components. Individual components of a product are listed in a matrix and interactions between those components are rated [20]. Identification of modules can be done using special algorithm, which cluster information included in the DSM. An example of an imaginary product presented by means of the DSM is shown in Fig. 1. The product consists of seven components (A-G). Original DSM is presented on the left side of the figure, and clustered DSM is presented on the right side of the figure. The interactions between components may vary in different directions. In Fig. 3, components C and D depend on component A, but component A does not depend on C or D, or any other component.

Interactions between components can be stored in different ways. In the current example, interactions are presented in a binary manner, showing whether interactions between components exist. Rating the interactions (e.g., -2, -1, 0, 1, 2) allows to show the strength and desirability of the connection. It is also possible to include information about the nature of the interactions by presenting connections in different domains. In practice, there are four domains that are often used to present information about products: spatial DSM (*Ds*), which shows relations in physical space and alignment, energy DSM (*De*), which shows the need for energy exchange, information DSM (*Di*), which shows the need for data or signals to pass between components, and material DSM (*Dm*), which shows the need for material exchange (Fig. 4). Combination of those four DSMs forms a complete DSM of a product.

$$D = \{D_s, D_e, D_i, D_m\} \qquad (1)$$

The dimension of the combined DSM (*D*) are *n* x *n* x *m*, where *n* is the number of components and *m* is the number of domains.

6.1. DSM for adaptable systems

Redesigning of a product for adaptability can involve change of the product parameters and/or their characteristics. Due to that change, a number of connections between components may change as well. It is also possible that some of the connections become more important for the functionality of the product than the other ones. It is, therefore, important to incorporate all those changes in the design of the adaptable products [20].

6.2.1. Action plans

Initially, engineers have to choose the adaptability instruments (e.g., parameters) of the product that will be made adaptable. Afterwards, action plans for adaptation of those adaptability instruments need to be derived taking various scenarios into account (e.g., environment changes, aging of the product). For each scenario, it is necessary to make an action plan, which describes (in detail) the moment and he way the product will adapt itself. An action plan will be executed by the product itself at the moment when the conditions or tasks will ask for that particular action plan.

6.2.2. Action plans and DSM

The original DSM of the product has to be expanded in order to deal with the action plans needed by the

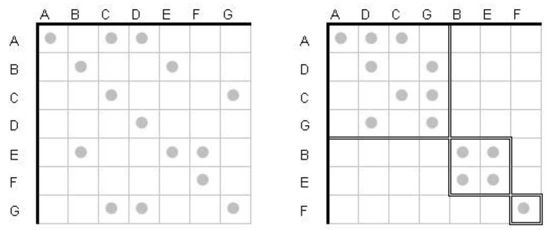

Fig.3. *Design structure matrix (DSM). Left – original DSM; right – clustered DSM.*

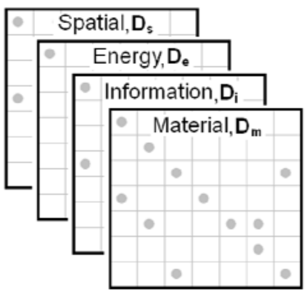

Fig.4. *Four domains of the DSM.*

product to adapt itself to different tasks and changes in the environment or product state. Original DSM, nevertheless, is still of importance, because connections in the original product will still be present in the adaptable product. In order to deal with the adaptability of the product, new layers need to be introduced to the original DSM. From this moment, the original DSM will be called *normal* DSM.

For each action plan, connections between components have to be listed in separate DSMs in four domains: spatial, energy, information, and material. A combination of those four domains gives a complete DSM for each separate action plan:

$$P = \{P_s, P_e, P_i, P_m\} \qquad (2)$$

The DSM for the *n*-th action plan is given by *Pn*.

Rating the interactions of each action plan has to be done very carefully, since it requires an expert knowledge. There is possibility that some of the interactions in an action plan DSM already are contained in the normal DSM. In such case, those interactions are more emphasized in the action plan DSM. Besides those interactions, action plan DSM consists of information about new connections between components.

In general, adaptable products will have multiple action plans. The *adaptability DSM* is created by combining information from each action plan DSM. As a result, the adaptability DSM will consists of the action plan DSMs (*Pn*) for all the action plans *N*:

$$A = \{A_s, A_e, A_i, A_m\} \qquad (3)$$

The *total DSM* (*T*) can be defined as a combination of the original (non-adaptable) product DSM and the adaptability DSM:

$$T = \{A, D\} \qquad (4)$$

Graphical representation of the total DSM is shown in Fig. 5.

6.2.3. Total DSM

To be able to run clustering algorithms, it is necessary to first combine interaction information stored in individual matrices into the total DSM. The normal DSM and the action plans DSMs are obtained by combining the spatial, energy, information, and material DSMs. The importance of each domain can be rated using weights:

$$D = w_s \cdot D_s + w_e \cdot D_e + w_i \cdot D_i + w_m \cdot D_m \qquad (5)$$

$$P = w_s \cdot P_{s,n} + w_e \cdot P_{e,n} + w_i \cdot P_{i,n} + w_m \cdot P_{m,n} \qquad (6)$$

In this paper, we use the same weights for the same domains of the normal and the action DSMs. For example, the weights w_e are the same for normal energy DSM and for the action plan energy DSM.

Adaptability DSM is formed by combining the action plans DSMs:

$$A = w_1 \cdot P_1 + w_2 \cdot P_2 + \cdots + w_N \cdot P_n \qquad (7)$$

The total DSM is given by:

$$T = D + A \qquad (8)$$

Interactions that are rated as ‘-2’ (undesired connection) in one of the DSMs and as ‘+2’ (required connection) in another DSM need special attention. Those connections cannot be added. They need to be individually addressed by engineers. It might be necessary to change, redesign or divide the component into two components in order to deal with contradicting interests. Another solution to this problem is reconfiguration.

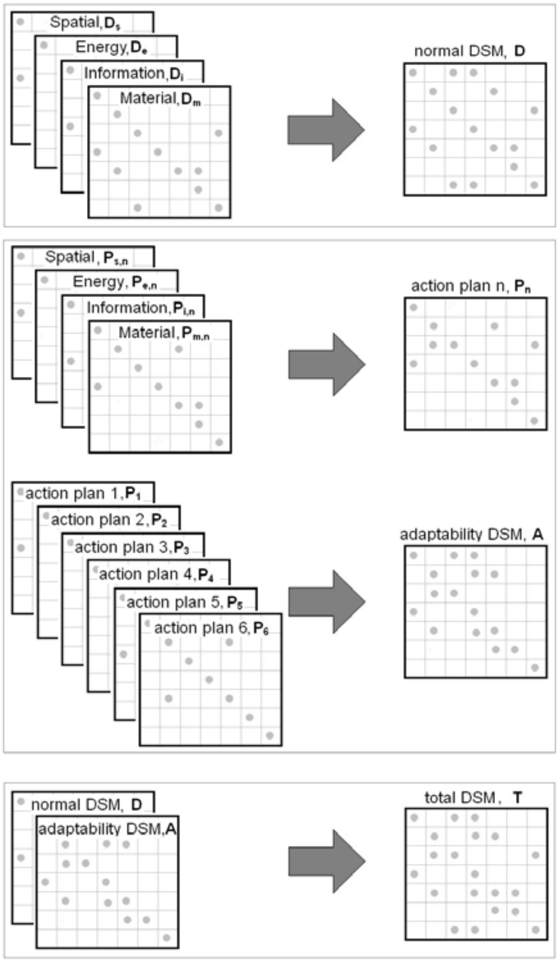

Fig.5. *Building the total DSM with normal DSM and adaptability DSM.*

Interactions that are rated as ‘-1’ provide information that there are some negative effects of that connection, but functionality of the components is not prevented. In case that ‘-1’ rating conflicts with a positive rating in another DSM, the likely negative side-effects should be carefully documented and addressed in the later stage of the design process.

6.2.4. Weight choices

The weights used to multiply the DSMs should be carefully chosen for each product and its DSMs. Only then it will be possible to arrive at a DSM that contains accurate information. Since weights strongly depend on the product, engineer, and company, there is lack of a general method for choosing them.

The choice of the weights should not be set for a product unless that choice is carefully motivated. On the other hand, it might be helpful for engineers to see how different weights influence clustering of the DSMs.

6.2.5. Clustering the total DSM

To group the product components into clusters, a clustering algorithm has to be applied on the total DSM. Identified clusters are the proposed modules for adaptable product. Optimal clustering for the adaptable product can be obtained by clustering the complete total DSM.

6.2.6. Runtime reconfiguration

Ideally, adaptable products should be able to reconfigure itself during runtime. There are two reasons for the product to reconfigure:

- there is one (or more) connection between components that are undesired for one of the action plans
- the optimal clustering for a partial total DSM containing a number of action plans is significantly different from the optimal clustering of another partial total DSM containing different action plans.

If configuration needed for the *n*-th action plan is different than those for the *m*-th action plan, adaptable product might reconfigure itself when going from executing the *n*-th action plan to the *m*-th action plan.

States of the product consist of action plans that have similar clustering needs. Each state contains multiple action plans. For each state, a partial total DSM has to be made. Action plans, which have similar clustering are included in one state of the product. Between different product states the product should reconfigure. It cases, it might appear that it is impossible to go directly from one state to another.

6.2.7. Including new components

In some cases, development of action plans results in need to include new components to the product. Those new components have to be included into the DSM. The normal DSM will have ‘zeros’ for those components. The DSM that corresponds to the action plan responsible for the new components will contain all the necessary information about the interactions of the new components. Adding new components to the DSMs will result in change of the dimensions of all the DSMs (including the normal DSM and every action plan DSM) and will contain new (but the same for all the DSMs) amount of components.

7. DISCUSSION

The goal of this paper was to present general aspects that need to be taken into account when (re)designing a product that automatically adapts to changing environmental and/or working conditions. According to that, we presented a general scheme for the adaptable product. The scheme is introduced in order to make a step to formalize a design method, which will help designers to design adaptable products. With this scheme, one obtains an overview of seven general components (blocks) of the adaptable product. Besides main connections between the components, the scheme shows which components are included in the product self and which ones are not.

In this paper, we focused on the design-time and runtime adaptability of the product. The scheme presented in Fig. 1 can be used to deal with adaptable architecture for both those adaptabilities. Design-time adaptability requires design patterns or (component) framework technology, which allows modifications by choosing, for example, implementation of specific sub-systems, or by integrating new sub-systems that expand its functionality. Our scheme can be used when designing product families, and product platforms considering the tasks, states, control and decision system, adaptability instruments, functional part of the product, and feedbacks as components of the framework.

The veracity of the scheme presented in Fig. 1 has not been validated in this paper. Therefore, our future work will focus on development of a large set of examples to test above aspects. Obtained results will show whether presented idea and concept of adaptability are correct. Moreover, it will become clear whether proposed scheme is suitable for all kind of adaptable systems or only for their specific classes (e.g., mechatronics and software types).

In this paper, we presented a method to deal with some aspects of the product architecture of the adaptable products. The method is especially useful for understanding and documenting the connections between components in an adaptable product.

Presented method is intended for large-scale complex products. Rating of connections requires expert knowledge of multiple engineers. In this case, the choice of the weight factors of the different action plans is becoming important. In a complex product more components have to be included. As a result, the connections between components can become more complex. The clustering will be different depending on the subjective rating of the interactions and the weight. Finally the clustering routine will influence the outcome of the clustering procedure.

Further research has to show to what extent the rating of the interaction and the weights of the adaptability action plan DSMs influence the clustering of components. Aside from the interconnections between components, there might be different reasons for some components to be in the same module. Those reasons have to be incorporated into this method by the engineers. It is recommended for the use of this method, to use different weights and compare the outcomes of the clustering routines. In this way, the engineers using the method can gain insight in the influence of the weights and in the connections between components and clusters. The engineer can subsequently make a decision upon the most profitable clustering and thus the best weights to be used for that product.

8. CONCLUSIONS

Adaptability is a relatively new concept in design. A standard design methodology has not yet been developed for adaptable products. The concept of product adaptability is not yet fully understood, since a standard definition of the concept is still lacking. In general, three types of adaptability are recognized: design-time, runtime, and lifetime adaptability. We focus on the first two types of adaptability. An overview of seven general components of an adaptable product is given using a general scheme. The main design choices are related to the control and decision system, and to the product architecture. The scheme may prove useful as a guide, or ‘checklist’, when (re)designing an adaptable product. In this paper a first step towards formalized design of adaptable products is described. We also presented a method that deals with several aspects of the adaptable product architecture. The method is especially useful for understanding and documenting the connections between components in an adaptable product.

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