Proceedings of the ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2008
August 3-6, 2008, New York, USA

DETC2008-49971

TOWARDS ADAPTABLE ARCHITECTURE

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ABSTRACT

There is a need for products that can automatically adapt to various environmental and working conditions. Since a standard theoretical framework for designing such adaptable products is not yet established, only few rules, generalized methods, software tools, and guidelines for design for adaptability can be found in literature. The goal of this paper is to address issues associated with designing adaptable product architecture and to propose a first step to develop methods and tools to deal with these issues. The paper first gives various definitions and an overview of product adaptability. Then it discusses adaptable product architectures, external conditions, and customer needs that are crucial aspects in designing adaptable products. The research proposes a scheme of an adaptable product that can constitute part of a formalized design method for adaptability. Finally, it illustrates the design choices that should be made to arrive at an adaptable product architecture.

INTRODUCTION

A highly dynamic market has increased competition for better product quality, functionality, features, customization, lower cost, shorter time-to-market and time-to-delivery, and environmental friendliness. Companies cannot rely solely on their past successes to survive in the current market. Therefore, it is imperative for them to bring in new products and features to the market and to respond to evolving customer needs. To do so, they need to be continually innovative [1, 2].

Shorter time-to-market enables the company to quickly react on changing customer demands as well as on technology and competition evolutions. Products should be easily modifiable, to take an advantage of new hardware and software technologies and to respond rapidly to changing customer expectations. This indicates the importance of technologies to improve evolvability of products, i.e., the ability to easily evolve in response to technology evolution, competition evolution, and customer expectation evolution. Currently, most of the development approaches specify functionality of the product during design-time. As a consequence, products operate reliably only within well-defined range of conditions (e.g., humidity and temperature of the environment). Therefore, these approaches are inadequate to develop products that can easily adapt or be modified to various environmental and working conditions.

A feasible answer to these new challenges is genuine product evolvability, i.e., the ability of the product to adapt to a wide range of working conditions, which are caused by user requirements changes and/or environment changes. An example of such a product can be a printer, which is used by a variety of users (e.g., at the office) and can be placed in very different environments (e.g., office, corridor, workshops). Our research project focuses on the design of adaptable printers. The project, called Octopus, is a joint project of a consortium of industrial and academic partners: Océ-Technologies B.V., the Embedded Systems Institute (ESI, www.esi.nl), and a number of Dutch universities.

There are practical and economical benefits in the ability of a product to adapt to various conditions. For example, it would be useful to have a printer that adapts to varying printing needs (e.g., plain monochrome text, full-color image) while maintaining constant high-quality print. Adaptation of the product would also be beneficial when a product is in good working conditions, but is put out of service (e.g., due to changes of user needs). For example, adaptation of a color printer to a monochrome printer would create new service life of the printer.

Since a standard theoretical framework for designing an adaptable product is not yet established, few rules, generalized methods, software tools, or guidelines for design for adaptability can be found in literature. In software and mechanical design, several methods for increasing system's adaptability are available [3-9]. Those methods, however, have been proposed taking different definitions of adaptability into account. Since design for adaptability strongly depends on the kind of adaptability, none of the above referenced methods can be consider as superlative for design for adaptability.

This paper focuses on aspects that need to be taken into account when designing an adaptable product. Following sections of the paper deal with the definition and classification of product adaptability. Also crucial aspects for adaptability, such as customer needs, external conditions, and product adaptability at various levels (e.g., subsystems) are described. A general scheme for an adaptable product is proposed. The concept is explained taking a printer as an example. The motivation for implementing adaptability into a printer comes from the fact that every print is unique (e.g., plain monochrome text, full-color image, various combinations of monochrome and full-color texts and images) and it results in a specific printer setup necessary to achieve the best performance (e.g., constant high quality print). In case of incorporating adaptability to the printer, the best performance at each unique print could be obtained when the system would reconfigure itself during printing.

ADAPTABILITY

Definition

In the literature, various definitions of adaptability can be found. These definitions, however, are different depending on authors. For example, Gu et al. describe design adaptability, and product adaptability [5]. Design adaptability refers to the design paradigm, which is defined as the ability of a product to adapt to new requirements by means of small design changes that do not require a lot of effort [5]. The product adaptability, on the other hand, refers to a product that is adaptable by the user [5].

Chung and Subramanian stated that adaptability refers to the ability of a system to make an adaptation; a change in the system to accommodate change in its environment [6]. They also described the three tasks that are involved during adaptation:

- Ability to recognize the change from an old environment to a new environment.
- Ability to determine the change that has to be made to the system (according to the recognized change in the environment).
- Ability to effect the change to generate the new system.

Olewnik et al. described an adaptable system as one of two modes of a flexible system [7, 8]. The flexible system is defined as a system that retains 'a high level of performance when operating conditions or requirements change in a predictable or unpredictable way' [7, 8]. Systems able to accommodate unpredictable changes in an operating environment are called robust. Systems that accommodate predictable changes are called adaptable. In case of adaptable system, the change that has to be made to the system can be done in real time (active) or when the system is not in use (passive).

Oppermann made a distinction between an adaptive and an adaptable system [9]. The adaptive system is able to modify its own characteristics automatically according to the user's needs. In the adaptable system, the system characteristics are modified by the user self.

Depending on the author, 'adaptability', 'flexibility', and 'reconfigurability' are used as synonyms. According to Rajan et al., product flexibility can be seen as the degree of responsiveness for any future change in a product design [10]. Such flexibility increases responsiveness to changing market demands while minimizes the amount of time required to redesign [10]. Flexibility is measured taking the number of parts, functions, modules, interfaces, and their types into account.

Ferguson and Lewis defined adaptability as means to achieve a reconfigurable system, in which variables that can be changed as well as the range of their change are identified to improve the performance of the system [11]. Reconfigurable systems have been defined (similarly to the flexible system defined by Olewnik [7, 8]) as systems designed to maintain a high level performance by changing (real-time) their configuration under changing operating conditions or requirements [11, 12]. The way the operating conditions and requirements change can be both predictable and unpredictable.

In this paper, we focus on ‘automatic’ adaptability of the product. Therefore, we define adaptability as system parameters (characteristics) that can be changed (adapted) to improve performance of the system in predictable situations. The parameters can be changed real time (active) or when the system is not in use (passive). The parameters can be changed only by the system self and not by the user.

Further in this paper, a printer is called adaptable when it is able to adapt to changing conditions, including user requirements and changing environment.

Classification

The goal of the adaptable product is to extend the utility of the product and its design. Utility of the product can be extended at different times; during design (design-time adaptability), when the product performs a task (runtime adaptability), or by prolonging product’s service life in its normal operational mode and by adapting it to new operational modes (lifetime adaptability).

Generally, adaptability of the product at the design stage is of importance to the producer, who can adapt the design to various requirements such that different products can be produced. The design-time adaptability, therefore, is related to reuse of the existing design in order to produce different products. Applicability of the design-time adaptability depends on the possibility of producing products with similar designs. In case that a product has a specific design that cannot be modified to produce new products, the design-time adaptability term is irrelevant.

Modularization

In the literature, various product configuration design approaches are described. The most common ones are: modular design, and product family and platform design. According to Holmqvist, modular design should be seen as one function that is allocated to one module [13]. This allows making changes in one module without requiring any change in other modules.

Marshall and Gu give a more general definition of modular design [14, 15]. According to them, modular design is a design methodology that aims at developing a product architecture consisting of physically detachable modules (units) [14, 15]. A combination of various distinct modules can accomplish diverse functions [16].

As said by Baldwin, modularity can be applied in design, production and use [17]. Baldwin describes the concept of modularity as parts that are designed and produced independently of each other, but which must function together as a whole. Since there are always interfaces between different modules, the modularization is described as a means that specify interfaces between these modules.

Holmqvist describes product modularization as grouping a number of components into modules and defining interfaces between these modules [18]. Product modularization should be done in such a way that design decisions in one module are isolated from those in other modules.

The main difference in the definitions of modularity is the way the product architecture is seen. In case that the product architecture is seen as a mapping between functions and components, the definition of the modularity is that one function is mapped into one module. In case that product architecture is described as grouping components, the definition of modularity refers to grouping of the components in a way that the interactions between components are optimal. These two definitions are fundamentally different and call for different methods to deal with the modularization.

In most research, the objective of modularization is to minimize the interactions between different modules or to make functions of a product independent by using a separate module for each function. It is, however, often impossible to achieve a complete decoupling in modularization. Therefore, tradeoffs have to be made.

Umeda et al. argued that the decomposition in modules can be different for different types of life cycle models [39]. Those include the reuse type, the recycling type or the maintenance type. The recycling type modules, for example, components made of the same material are grouped together.

Qureshi et al. calls a few principles that can be applied in order to achieve product flexibility [18]. They did not, however, provide a scientific background for the statements. Nevertheless, it seems to be useful to consider the usefulness of these principles in the field of adaptable products. For the modularity group, Quershi et al. proposed following principles:

- To use a different module to carry out each different function.
- To divide each module into a number of smaller, identical modules.
- To collect parts, which are not anticipated to change in time into separate modules.
- To collect part, which perform functions associated with the same energy domain into separate modules [18].

These principles can be seen as modularization objectives that can help the designer to develop an adaptable product.

During (re)design for customization, a change to one part of the product can result in changes to other parts of the product. Prediction of such change and its propagation would be of great help when (re)designing complex products. Presently, the nature and extent of change propagation is not completely understood nor predictable [19]. Clarkson et al. showed that Design Structure Matrices (DSM), known design method used to store information about connections between components and modules in the product, can be used to provide indication as how change may propagate through a product [19]. Proposed by Clarkson et al. mathematical model can be used to predict the risk of change propagation in terms of likelihood and impact of change [19].

There are various advantages of modular design. One of them is the fact that careful product modularization allows using the design of earlier products in new products without any changes. Modular design can also be used as a help to produce products with minor variance. Additional modules added to the product can result in new products. Moreover, some of the modules can be reusable or remanufacturable. Modular design, therefore, is beneficial for various aspects of product life cycle; design, assembly, services and recycling [20, 21].

Product family and product platform

Product family can be defined as a group of related products that is derived from a product platform in order to satisfy market niches [22]. Product platform has been differently defined by various authors. Meyer and Lehnerd described product platform as 'a set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched' [23]. According to McGarth, product platform is 'a collection of common elements, especially the underlying core technology, implemented across a range of products' [24]. Robertson and Ulrich define product platform as 'the collection of assets (e.g., components, processes, knowledge, people and relationships) that are shared by a set of products' [25].

Robertson and Ulrich provided general and abstract definition of product platforms [25], while Sanderson and Uzumeri provided a definition that is industry and product specific [26]. Besides that, there are different meanings of platforms; there are definitions and descriptions that focus mainly on product itself [27], whereas other authors try to investigate the platform concept in terms of a firm's value chain [28].

Generally, a platform is any set of standardized parameters, which are maintained within a group of products [29, 30]. There are: process and manufacturing platforms, component standard platforms, and modular platforms. According to Gu, the process and manufacturing platforms are the cases where the platform is not so much integrated into design of product family. It is, however, integrated into the process of product manufacturing (the way that product is built) [5]. The component standard platforms combine manufacturing issues in multiple products by using regular components whenever possible. Modular platforms are different from the process and manufacturing platform, and component standard platform, because they make use of modules between several products. In this way, common parts are used wherever it is possible [31].

Each product has its service life. In case of deterioration, damage, aging, etc. of the products, the functions of the products are not anymore satisfactory delivered. Service life of such products, however, could be prolonged. Marakeset proposed two methods of prolonging the service life of the product: designing out maintenance, and designing for maintenance [32]. Designing 'out maintenance' products is strongly influenced by the quality and robustness of the product. Design 'for maintenance', on the other hand, involves studies on possible failure scenarios, risk analysis, and manufacturing supplies for easy disassembling and reparations of frequently deteriorating components.

This paper focuses on design-time and runtime adaptability. In following sections, a general scheme for an adaptable product is proposed and main design choices are discussed.

GENERAL SCHEME FOR ADAPTABLE PRODUCT

A general scheme for an adaptable product is presented in Fig. 1. As a starting point of the research, we derived this scheme based on the well-established philosophy behind control engineering. Two main components in the scheme represent parts of the product that are responsible for taking actions depending on the input information. These components are visualized using ellipses. The remaining components in the scheme are inputs and outputs of the two main components. In Figure 1, these inputs and outputs are depicted using rectangular boxes.

The following sections of the paper provide definitions of each component included in the scheme. After these definitions, design choices are presented.

Tasks

Tasks are considered as an input for the control and decision system of a product. Tasks are defined as user demands. In case of a printer, an example of a changing task can be a change from printing a monochrome text to a full-color image print. In both cases, printer behaviors are different. Tasks often demanded by the user and the company that produces printers are: one and two-side printing, the quality of the print, contrast, and speed of printing.

States

Similarly to the tasks, states provide input information for the control and decision system of the product. The difference between the tasks and the states is that the states are not directly introduced by the user. The states are measured by the product itself. The states give information about the system itself and the environment. An example of the state for the printer can be the temperature of the environment, humidity, the temperature of the product components, energy consumption, the number of papers left in the printer, and the amount of toner left. Other important information included in the states is aging and deterioration of the system (e.g., state of the components), and pattern of usage (e.g., the amount and frequency of prints made per day).

Control and decision system

The control and decision system of the adaptable product is responsible for recognizing any changes in the input information. Based on the recognized change, the control and decision system determines an action that has to be done by the

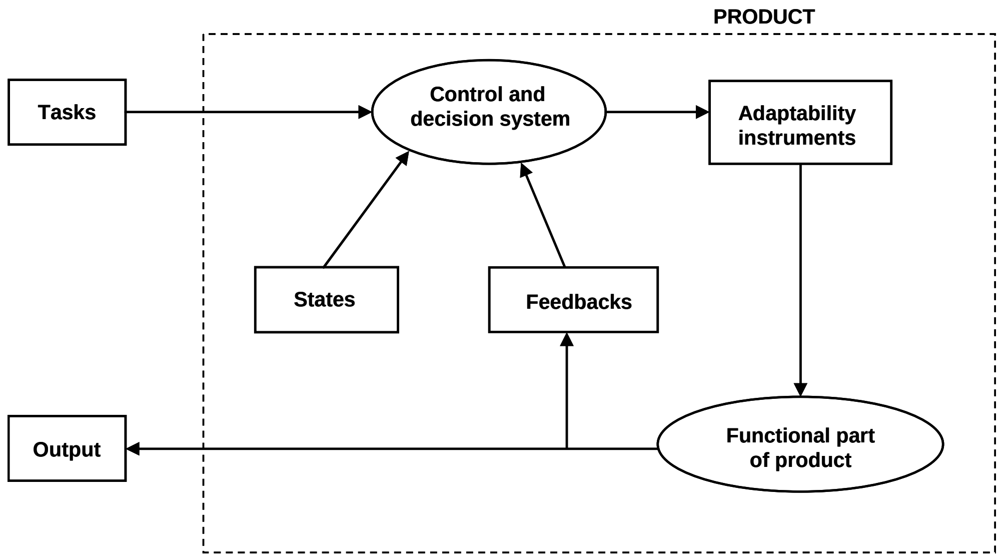

Figure 1. SCHEME FOR AN ADAPTABLE PRODUCT.

product. This requires appropriate ‘action plans’ for the product to perform adequate operations against changing conditions.

In case of a printer, a change of the printer job from monochrome text-only printing to a high volume full-paper full-color image print, for example, results in changed behavior of the printer. To maintain a high quality output, it is necessary to have an action plan for the real-time controllers.

Adaptability instruments

Based on the input information (e.g., tasks and states), an adaptable product has to adapt to changing conditions. This can be done using ‘adaptability instruments’. Adaptability instruments are passive and are defined as a list of all possible instruments that are available for the control and decision system to adapt the product to changing conditions. This list includes simple parameters (e.g., speed) as well as more complex actions (e.g., reconfiguration of the system). In other words: everything that can be modified by the control and decision system in order to adapt the product to changed working conditions is called adaptability instrument. The adaptability instruments determine to what degree the product can be modified.

Functional part of the product

The functional part of the device refers to the part of the device that actually executes the work that has to be done. In case of a printer, the functional part of the device is the part that reproduces an image or text on the paper and any mechanisms to support this function.

Feedbacks

Feedback is defined as sensory information about the output of the product. It is an input for the control and decision system of the product. In case of a printer, feedback can be information about the quality of the print. For example, a sensor can measure the contrast of the print at the specific location. Speed of printing is also seen as feedback. Note that user input is not considered as feedback, but as a task.

In order to use feedback in the adaptable product, measures of the output have to be defined. These measures will be specific for the product, designer, and the company. Presently, most of the products do not contain feedback. When (re)designing an adaptable product, it is useful to include feedback in the product, because it gives valuable information about the quality of work done by the product. This information together with the tasks and states gives more accurate input for the control and decision system.

DESIGN CHOICES

The tasks given to the product and the output obtained from the product are mostly defined by the market requirements. Therefore, the tasks and the output do not leave many possibilities for the design choices. In Figure 1, a general scheme for the adaptable product is presented. This scheme consists of seven blocks. Except for the tasks and output

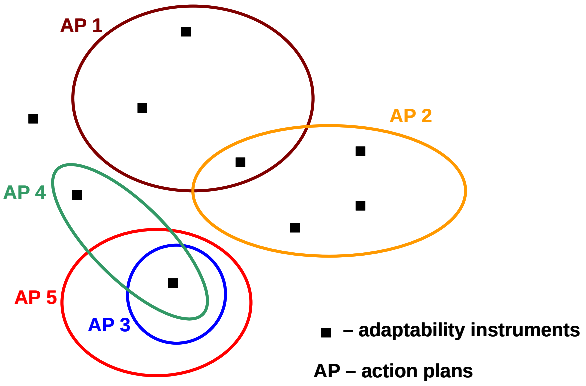

Figure 2. POSSIBLE RELATIONSHIPS BETWEEN VARIOUS ADAPTABILITY INSTRUMENTS AND ACTION PLANS.

blocks, all the blocks included in the scheme are design choices.

When designing an adaptable product, the designer has to decide:

- Which methods should be implemented in order to control the system and to decide what actions should be taken in order to make the product adaptable?
- What input information for the product is needed in order to make the product adaptable? Thus, the decision on the states and the feedback has to be done. Based on that decision, a selection of the amount and type of the sensors can be done.
- What possible instruments to response to the input should be used? Hence, the decision on the adaptability parameters has to be done.

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

All the design choices should be done such that the output of the product satisfies the user and company requirements.

Design of control and decision system

When designing an adaptable product, the designer should foresee the changes that can occur in the environment and/or working conditions of the product. Then, action plans for the product have to be derived. An action plan is a list of all the tasks that should be carried out in order to achieve an objective. The action plans for the adaptable product are used to execute reorganization/reconfiguration operations against changing conditions of the product, including task changes, environmental changes, aging, and deterioration. To be able to describe those action plans, understanding of these conditions is required.

The decision on *how* and *which* adaptability instruments are used to adapt the product is made by the control and decision system according to the action plan derived for this specific change. Each separate adaptability instrument can be used in various action plans, alone or in combination with other adaptability instruments. Figure 2 presents a possible relationship between various adaptability instruments and action plans. Closed curves depict action plans. Squares represent adaptability instruments.

The action plans make use of the list of adaptability instruments. They are also used to control real-time actuators, which are used to maintain a high quality output. For example, in case that there is not a lot of toner left in the printer, parameters such as the amount of toner used for printing one letter, the amount of toner used per second, or the resolution of the print can be changed. When the quality of the print should still be kept constant, the speed of printing can be adapted.

Input about rising temperature of the environment can result in turning on a cooling mechanism of the printer. The cooling is then an adaptability instrument. Also power safe and speed of printing options can be adapted based on the input information.

In each product, tradeoffs have to be made. A tradeoff refers to a situation, in which one objective (e.g., quality) must be decreased in order to increase another objective (e.g., cost). This implies a decision that has to be made with full comprehension of both advantages and disadvantages of a particular choice.

For adaptable products, it has not been yet investigated how the tradeoffs should be made. An important economical concept, which found broad application in game theory, engineering, and social sciences is Pareto efficiency (or Pareto optimality) [33-35]. Pareto efficiency can be used as a formal framework for tradeoff studies between desirable product attributes. The desirable criteria for the printer would be (among others): quality, speed, and cost of a print.

Finding Pareto frontiers is useful when designing an adaptable system. Yielding all of the potentially optimal solutions (indicated by the Pareto frontier) can be used by the designers to focus on tradeoffs within restricted set of parameters, rather than considering the full range of parameters. When designing an adaptable system, the aim will be to move between different objectives along the Pareto frontier. When two objectives are considered, the Pareto frontier can be visualized. In Figure 3, a representative (imaginary) Pareto frontier, two objectives, and two points (A and B) are presented. Point A is placed at one end of the Pareto frontier. This point is optimized (minimized) for objective 1. Point B is placed at the second end of the Pareto frontier and is optimized (minimized) for the objective 2. The points between the end points of the Pareto frontier stand for tradeoffs made between the objectives. The distance between extreme points that system can operate in is a measure of the flexibility [7, 8].

In case of a printer, power consumption can be seen as the objective 1, and time taken to print one page as the objective 2. Theoretically, moving along the Pareto frontier results in optimal performance of the printer. Ferguson and Lewis, however, reported that following the trajectory depicted by the

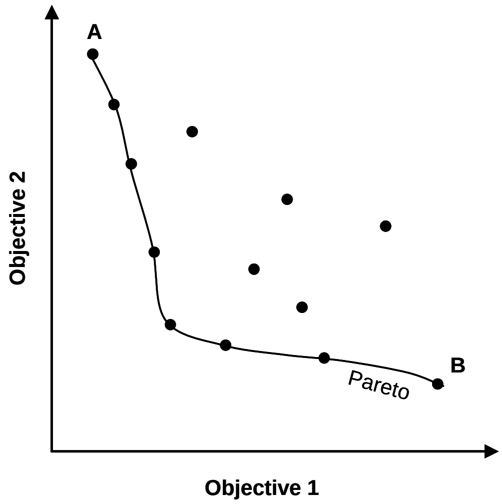

Figure 3. AN EXAMPLE OF PARETO FRONTIER – ADAPTED FROM OLEWNIK [7, 8].

Pareto frontier might be unsatisfactory when designing reconfigurable systems, since changes in configurations take time and development of a controller would be very complex [11].

When more than two objectives are taken into account, the visualization of the Pareto frontier is difficult. Mathematical calculations on optimality, however, can be done in multiple dimensions.

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

To find optimal product architecture for adaptability, product architecture has to be investigated at various levels (e.g., subsystems such as printer engine, paper storage, and feeder), units (e.g., paper feeding, image transfer), and components (e.g., paper feeding belts, driving shafts, sensors, actuators). For instance, when speed and energy consumption has to be traded off among the units that constitute a printer engine, it should be investigated what the best subdivision of units is and how to achieve it (e.g., through hardware reconfiguration, controller (software) reconfiguration, or through central control or distributed autonomous systems architecture).

A printer that prints on two sides of the paper at once (duplex print) is used as an example to explain the way the adaptable architecture of the product works. Figure 4(a) shows the situation when the printer works correctly. The output of the printer is simultaneous print on two sides of the paper. Two cylinders in the figure illustrate upper and lower drums with toner. Figure 4(b) and (c) show the situation when the upper drum cannot perform printing due to lack of the toner (indicated by crosses in the figures). The drum itself, however, is not broken and can still be put in rotational movement. The printer can be reconfigured such that the task will be performed using one (working) drum only. The printing task involves then printing only one side of the paper at the time and is done in two steps. First, one side of the paper is printed using the lower drum (Fig. 4(b)). To be able to print the second side of the paper, a change in the paper flow has to be made. An example of such a change is presented in Fig. 4(b). The ‘returned’ paper is positioned such that its blank side faces working drum (Fig. 4(c)). The blank side can now be printed by the working drum, as shown in Fig. 4(c). Above described reconfiguration of the printer will make printing process slower, but required function of the product (duplex printing) will continue.

Above described case can be presented by the general scheme for adaptable product. The task of the printer is to make a two-side print. The states provide information about toner shortage in the printing component. Based on these inputs, the control and decision system chooses action plan based on ‘if then’ rule. The parameter that is used to choose one or two-side printing (instead of two-side printing) is a means of the adaptable instruments. The remaining printing component serves as the functional part of the device. The output of the printer is a two-sided print.

Umeda et al. presented a model of a self-maintenance machine, which benefits from functionally similar components when faults occur [36, 37]. A self-maintenance of the product can be achieved in two ways: by adjusting its attributive state to maintain the behavior and function or by reconfiguring its behavior to maintain its function [38]. The first type of adjustment is called control type self-maintenance, and the second one – function redundant type self-maintenance. The first type of the self-maintenance uses an embedded model-based reasoning system to diagnose faults and to repair planning by means of sensors and actuators. The later type of the self-maintenance is achieved through potential functions of existing parts used in a different way (to some extent) from the way they are used in the original design.

Similarly to the printer example, the performance of the self-maintenance product can degrade, but required functions of the product will continue [39]. Above described examples show that the components of the product can be designed in such way that they can be used to solve adaptability and maintenance problems in adaptable products.

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 proposed a general scheme for the adaptable product. This scheme, although explained using a printer as an example, is a general scheme, which can be used for various adaptable products.

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.

As said in the Classification section, utility of the product can be extended at different times. 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.

In this paper, we did not validate the veracity of the scheme presented in Fig. 1 neither its usefulness as a part of an industrial design process. Therefore, our further 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).

Due to the multi-disciplinary design of the product, the interactions between various components can occur. Moreover, in some cases information about the states (e.g., the amount of the paper left in the printer) can be obtained from the functional part of the product (e.g., based on the number of prints done) and not from the sensors. These cases are specific for the product and should not be used to define a general adaptable product. Therefore, we focused only on the main interactions (connections) between the components in the presented scheme.

Presently, evolution of products, especially mechatronics products such as printers, leads to their increased complexity. This complexity is a result of integration of various disciplines in the product [40]. A multi-disciplinary design of products can lead to some problems when (re)designing for an adaptable product. For example, when designing a product, it is common that subprojects are carried out by designers, technicians, and manufacturers who are experts in different disciplines (e.g., mechanics, electronics, and software engineering). In the beginning stage of each project, the requirements that have to be satisfied are known. It is, however, often not know which specific parameters from one discipline (e.g., temperature) should not interfere with parameters from different disciplines (e.g., mechanical component of the product). Therefore, it is common that the designers overlook some of the parameters when designing a product. This results often in new problems to be solved or in necessity of redesigning of the product. Unfortunately, this kind of problems may often occur when designing complex adaptable products and/or when modifying existing products to become adaptable ones. For that reason, the action plans should be very carefully formulated for each individual scenario and evaluated before applying them to the product. Only accurate action plans for various operational conditions (various scenarios) will result in high-quality outputs of the product.

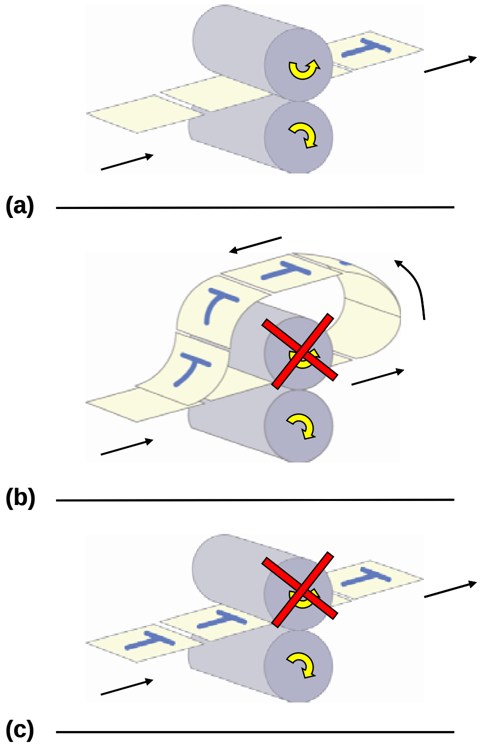

Figure 4. AN EXAMPLE OF ADAPTABLE ARCHITECTURE OF A DUPLEX PRINTER. (a) BOTH PAPER SIDES ARE PRINTED AT ONCE, WHEN THE PRINTER FUNCTIONS CORRECTLY; (b) THE UPPER DRUM DOES NOT WORK, SO THE PAPER IS PRINTED USING THE LOWER DRUM AND TRANSPORTED BACK SUCH THAT (c) THE OTHER SIDE OF THE PAPER CAN BE PRINTED.

CONCLUSIONS

In this paper, a first step towards formalized design of adaptable products is described. A literature survey on adaptable products and design demonstrates that there are various definitions of 'adaptability'. 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.

ACKNOWLEDGMENTS

This work has been carried out as part of the OCTOPUS project with Océ-Technologies B.V. under the responsibility of the Embedded Systems Institute. This project is partially supported by the Netherlands Ministry of Economic Affairs under the Bsik program.

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