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A FRAMEWORK FOR BUILDING BEHAVIORAL MODELS OF TECHNICAL AND ECONOMIC SYSTEMS

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ABSTRACT

Efforts towards a circular economy, increased possibilities of sensor technology and monitoring, and the developments in smart, connected products and systems have all contributed to the shift from selling products towards selling service-based offerings. Product-service systems are one example of service-based offerings, combining physical products or systems to service-based earnings logic.

Many traditional companies might benefit from exploring the possibilities of service-based offerings, but the tools for modeling, simulating and analyzing service-based offerings are somewhat lacking. There are numerous existing methods for modeling products on one hand, or business and economic models on the other, but fewer combining the two. This article presents a modeling framework for describing, analyzing and simulating offerings consisting of interdependent technical systems and business processes, based on a an extension of previous work on the Dimensional Analysis Conceptual Modeling (DACM) framework.

The goal of the framework is to allow modeling combinations of technical systems and business processes, resulting in flows of revenue between the stakeholders over a period of time. Further, the framework can be used to identify objectives of the stakeholders, and identify contradictions on a variable level, or conflicting objectives on a system level, and to propose solutions for solving the conflicts and contradictions based on general solution principles. In the article, the framework is applied on a case study of designing a reverse vending machine.

INTRODUCTION

Resource efficiency and circular economy have become more important drivers in the industry during the last decade or so (European Commission, 2014). One result of this development is increased interest towards service-based offerings both, in research and in the industry. Although many domains are moving increasingly towards pure services and digital, immaterial offerings, physical products are still needed in most of the technological fields.

Product-service systems are one example of a concept that combines physical products to service-based business. The underlying idea of product-service systems is the shift towards selling benefits or outputs that the customer values instead of selling the physical products or tools that the customer could use themselves to realize the benefits (cf. *buying a number of holes when you need them* vs. *buying a drill*). Selling output, benefits or customer value can enable creating higher-value offerings, increasing material efficiency, and e.g. ensuring steady revenue flows to the PSS provider.

The shift towards service-based offerings has, however, also potential drawbacks. For instance, the power distribution in a business relationship tends to tilt towards the seller in service-based business, more so than in traditional good-based business. This is mainly due to the changes in the product ownership. Also incentives of the buyer and the seller may be significantly altered, and extending the seller's responsibility to the usage phase further increases the complexity of the offering as a whole.

In order to facilitate exploring the possibilities of service-based offerings for a company operating in traditional product-based business, it should be possible to analyze, prototype, or simulate the offerings consisting of both physical products and services, and their differences in comparison to the current offerings. Moreover, when proposing an altered earnings logic or a business new model in a new product development project, the business case of the new offering should be presentable and preferably simulatable for the decision making process for the development process to even start.

On one hand, methods exist for building behavioral models of physical systems, such as simulation environments offered by CAD-tools, modeling languages such as Modelica, or multi-body simulation tools, such as ADAMS. On the other hand, business processes can be described using conceptual business model representations, such as Business Model Canvas, the revenue streams can be simulated using e.g. spreadsheet calculations or System Dynamics models. However, these methods usually either simply describe the systems in question in qualitative terms, or alternatively, they require in-depth knowledge and data about the application in order to be executable, simulatable models.

This article presents developments based on a modeling framework named DACM for describing, analyzing and simulating interdependent technical systems and business processes. The central research question here is *how to build behavioral models of combinations of technical and economic systems using design variable information available in the design phase?*

The article presents an extension of previous work on the DACM modeling framework (Coatanéa, 2015) for allowing the inclusion of also economic aspects.

The framework is essentially a functional representation of the value network with the central stakeholders, showing the states and the variables governing the transformations between the functions.

The framework includes:

- the different stakeholders of the value network relevant for the business model
- the different functions of each stakeholder or related technical system
    - the functions create value and cause costs
- the money flows between the stakeholders
- the value propositions of each stakeholder, which act as a basis for the money flow
- the logic triggering or activating the functions, and
- the connecting variables between the constituents of the model.

The approach is useful especially for estimating and comparing the potential behavior of offerings consisting of combinations of physical systems, services and business models with different earnings logics.

The goal of the behavioral modeling framework presented in this article is to allow *modeling and simulating combinations of technical systems and business processes*, resulting in *flows of revenue between the stakeholders* over a period of time. Further, using the model, the framework can be used to identify objectives of the stakeholders, and identify *contradictions on a variable level*, or *conflicting objectives on a system level*, and to propose solutions for solving the conflicts and contradictions based on general *solution principles*.

Contributions

The main contributions of this article include firstly, incorporating economic aspects to the bond graph representation and the DACM framework; secondly, introducing grafcet-based logic models for describing the sequence of the functions in a DACM framework; proposing an updated DACM approach for function-based modeling of combinations of physical systems and services; and, introducing the detection of contradictions between model elements using the causality information as an aid in designing combinations of products and business models.

BACKGROUND

This section provides background information for the topics developed in this article – firstly, the relevance of the topic in the context of the case study; secondly, existing approaches for modeling engineering systems; and thirdly, existing approaches for modeling economic systems and business models.

Product-service systems

The reason for targeting the concept of product-service systems in this article is that it is a useful and popularly used concept when discussing about complex offerings with earnings logic dissimilar to traditional product sales.

According to popular PSS definitions, a product-service system should:

- be a combination of products and services that fulfills a user’s need (Goedkoop, Van Halen, te Riele, & Rommens, 1999);
- increase dematerialization by:
    - focusing on the service element of the offering (Goedkoop et al., 1999), and
    - concentrate on selling use rather than products (Baines et al., 2007; Mont, 2002);
- be designed in an integrative manner (Meier, Roy, & Seliger, 2010) to form a value creating *system solution* (Mont, 2002);
- include the *product-service* as well as the infra- and governance structure needed for producing the product-service (Tukker & Tischner, 2006);
- enable increased total customer value through selling the *utility* of the assets rather than the assets themselves, which leads to potentially valuable changes in the distribution of risks, responsibilities and costs (Baines et al., 2007).

In a nutshell, in this article we refer to *product-service systems* when discussing physical product(s), used to create value, combined with a value, use, or output-based business model, especially when the two are designed as a whole concurrently.

Why then should we make efforts to allow combining technical and economic models in PSS design? Naturally, existing products can be combined with a service-based business model for delivering value or outputs to customers. But in order to reach a *system solution*, the physical product and the related business model should be designed concurrently, allowing feedback and iterative steps between the product design and business model design processes. Whether the service-based business model makes sense or not in a given context depends on a combination of multiple factors, perhaps even minor details, in the design of the physical system and/or the business model. In case we have a modeling framework that allows describing, analyzing and simulating the combination in the same model, it should greatly facilitate designing product-service systems.

Commonly used engineering system models

There is a wide array of different ways for modeling engineering systems and describing design problems. Traditionally, the models have concentrated on physical elements of the system, and as a consequence of the increase of use of information technology in technical systems, the models have had to incorporate also elements such as logic, information flows etc.

CAD models are perhaps the most useful means for describing the physical system and its mechanics and appearance. Based on the CAD models, one can build quite detailed simulations about e.g. the structural integrity using finite element method, or the dynamic behavior of the system and its parts using multi-body simulations. However, these approaches require in-depth knowledge and details about the structure, materials used, external loads, etc.

During the earlier phases of the design process, one can start drafting the architecture of the system and the interactions between the different parts of the system using for example SysML, functional representations, state charts, bond graphs, etc.

In the case of the functional representations, multiple architectural characteristics can be considered:

- Flows of different energies between functions can be represented,
- Types of transformations taking place in the functions,
- Types of connections between functions.

This modeling approach is proposed in multiple reference books in engineering design such as Pahl and Beitz (Pahl, Beitz, Feldhusen, & Grote, 2007) or Otto & Wood (Otto & Wood, 2001) or in System Engineering such as the Incose handbook (Haskins, Forsberg, & Krueger, 2006). The modeling approach presented in those books is not always taking into account control aspects so important in most of the modern systems.

Consequently the Pahl and Beitz modeling method is adapted mainly to mechanical systems. Modern systems are less and less purely mechanical. There is a need to also integrate concepts such as transitions or Boolean conditions to expend the scope of modeling approach using functions to wider type of engineering systems. The control science has developed a set of theories and methods used to model and design discrete and continuous systems. Different types of fundamental systems categories have been underlined such as first and second orders systems for example. Languages dedicated to different control technologies capabilities such as PLC systems or computers have been developed. Those languages are for example Petri Net, Grafcet (a specific category of Petri Net) (de l'Électricité & Norme, 1982), high level modeling languages such as IDEF or SysML diagrams such as the state charts (Bravoco & Yadav, 1985) (OMG, 2008).

The DACM framework introduced by Coatanéa (Coatanéa, 2015) uses the functional modeling method as an initial material to generate a model that can be simulated. To obtain a level of description where simulation is becoming possible, the DACM framework is transforming the input provided in form of the functional model and Grafcet into multiple stages.

The DACM framework utilizes dimensional analysis in building the behavioral laws from a causal graph and its associated set of units. Dimensional analysis is an approach for reducing the complexity of modeling problems to the simplest form before increasing the level of details with any type of qualitative or quantitative modeling or simulation (Bridgman, 1969). The fundamental interest of DA is to deduce relationships of system variables via studying the dimensions of the variables (i.e. length, mass, time, and the four other dimensions of the international system of units).

The central idea is that limited supplementary information and skills should be needed to enrich the functional description. Indeed, one central requirement for the DACM framework to become useful and widespread in the engineering community is that information needed to generate such type of model should be extracted as much as possible automatically or semi-automatically from a functional description and from a grafcet representation of the system's conceptual solution. This is imposing to build in the DACM framework an ontology describing the fundamental steps of this transformation process. This project is currently going on and several of those elements have already been developed. The key transformation steps are the following:

1. Automatic extraction of key design parameters,
2. Automatic Causal ordering of those parameters based on the functional topology,
3. Automatic generation of the behavioral laws associated to the causal graph using the measuring of the variables,
4. Automatic generation of the Boolean laws required to implement the transitions rules described in the functional models using the Grafcet representation

A prototype tool already exists to automatically support the most important steps 2, 3 and 4. The tool is intended to facilitate the industrial adoption and usage of DACM, since using the method with the software tool would require no specific mathematical or e.g. programming skills.

of the conceptual solution under investigation. Causal graphs are used to model the architecture of the system. An ontology has been developed to capture the knowledge associated with the DACM modelling process.

The DACM framework can be used to compare *Reusable models Primitives* (RMP) and extract parts of existing RMP that can be reused in a new problem situation. It can also analyse existing models and be used to organize the re-engineering process.

Another benefit of the approach is to provide an initial low-precision simulation model of the envisioned conceptual solution for solving the problem. Using this low-precision simulation model, the DACM framework is able to locate and specify areas of the solution model where supplementary simulations or experiments are needed to increase the knowledge of the system under investigation.

An additional use of the method tested in the article is the search for existing design conflicts in a design architecture. In case a contradiction is discovered using the causality information, different *generic solution principles* have been developed in DACM been for removing the contradiction. The generic solution principles are initially inspired by the inventive principles of TRIZ, and they include re-examining system boundaries, combining multiple systems for acting on a contradiction, redesigning the graph for decoupling coupled elements, or redesigning the graph for aligning the objectives; however, the length and scope of this article does not allow presenting the principles in a more detailed manner.

CASE STUDY: A PRODUCT-SERVICE SYSTEM

The proposed framework for behavioral modeling of product-service systems is applied in this section to a case study of a *reverse vending machine*.

Reverse vending machines (RVM), shown in Figure 7, are devices designed to facilitate returning and recycling different artifacts. They accept recyclable items and reward the user based on the amount of items accepted for recycling. Most often the term reverse vending machine refers to the recycling of empty beverage containers, mainly plastic and glass bottles and aluminum cans, but RVMs have been developed also for batteries, light bulbs, and e.g. used cellphones (Tanskanen & Takala, 2003). *Deposit-refund systems* are among the best incentives for consumers to recycle solid waste (Calcott & Walls, 2005), and reverse vending machines are the main enablers of a deposit-refund system. RVMs are used in many European countries and also e.g. in some states in the USA, and they are often located in grocery stores or recycling centers.

This article presents research based on an in-depth study of a single PSS design case, a commercialization project funded by *Tekes*, the Finnish Funding Agency for Innovation between 6/2013 – 1/2015. Based on the results of related previous projects, the goal in the project was to develop a recycling system for empty beverage containers for grocery stores. RVMs operate in demanding conditions, and according to the service provider and personnel interviews made during the project, reliability of the RVMs is often a problem in practice. Downtime and unavailability of the systems cause direct and indirect losses of earnings for the grocery store.

Figure 7 An illustration of an example structure of a reverse vending machine - the physical structure designed during the RVM design project.

The main goal in the design was to create a system that would facilitate higher availability and reliability while minimizing the life cycle costs of the RVM.

Model of the RVM-related value network

The value network surrounding the RVM provider and its customer, the grocery store, is used here as a case study for presenting the DACM approach applied in a context of economic interactions in a value network. Figure 8 shows an illustration of the value network. The value network representation includes altogether seven stakeholders, three of which are considered as stakeholders of interest in the analysis; the others illustrated as clouds similarly as in system dynamics representation. This allows representing a more comprehensive view of the interactions in the network while excluding the functions and the variables internal to the less interesting stakeholders.

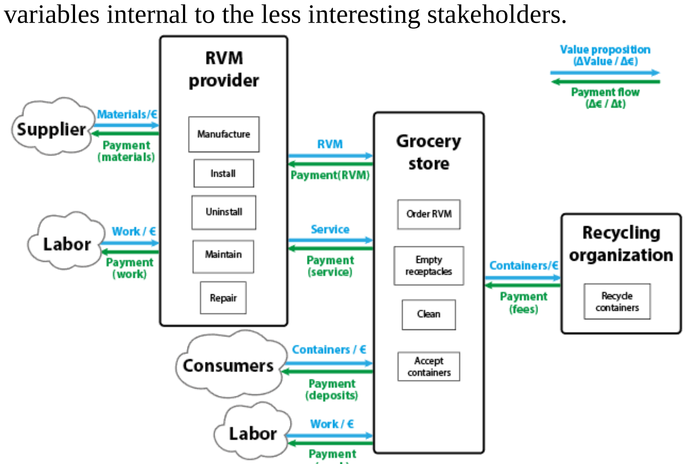

Figure 8 The model of the RVM-related value network showing the stakeholders, their functions, and the transactions between them.

The stakeholders of interest here include the system or RVM provider, grocery store and recycling organization. Figure 8 shows the value network in the traditional product-based business. The RVM provider buys materials and work for manufacturing RVMs and for installing, maintaining and repairing them, and sells first the machine and then the maintenance service to the customer, the grocery store. Consumers bring empty bottles and cans to the grocery store in exchange for money, and the grocery store buys work for its functions, and basically sells the returned containers for recycling.

The functions are in practice governed by a number of variables, and also the stakeholders have internal variables such as revenue, operational income, etc; these are visible in figures 10 & 11. Now, using the Grafcet representation of the system functions and applicable causal rules, shown in Figure 9, we can show the causal relationships between the variables of the functions and the stakeholders. The Grafcet model is used to describe the logical sequence of the functions and the transitions between the functions.

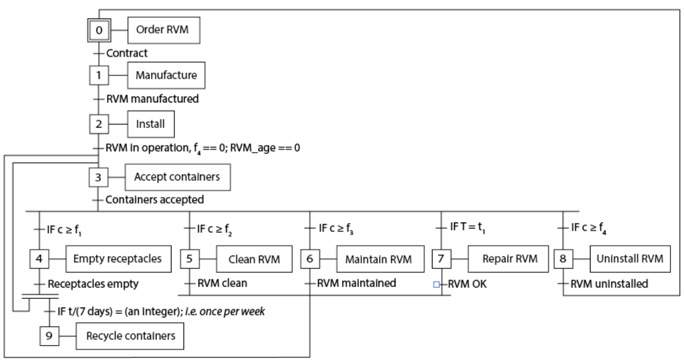

Figure 9 Grafcet representation showing the logic of the different functions included in the model.

In this part of the article we limit the scope of the analysis to studying only a subset of the network – mainly the grocery store and the RVM provider as shown in Figure 10. Now, with the causal model of the variables, we can already gain insight about the value network. If we analyze the network from perspectives of different stakeholders, we can, firstly, identify their main objectives in the scope of the analysis, and secondly, propagate these objectives in the network of variables using the causality information.

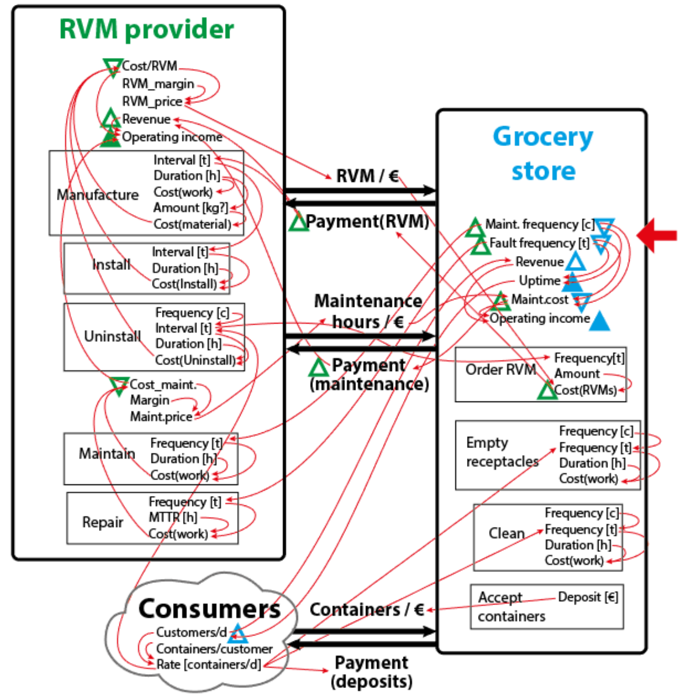

Figure 10 A subset of the value network model including the central stakeholders, their transactions, and the causal relationships between the variables. In addition, the objectives of the stakeholders are indicated with triangles; upward-pointing triangle indicates an objective *to maximize*, and downward-pointing *to minimize;* a solid triangle represents a direct objective, and a triangle outline a derived objective.

The causal relationships presented in red in the figure above can be obtained using a specially developed algorithm presented briefly in the *Method*-section of this article.

Figure 10 shows also the objectives from the perspectives of both stakeholders of interest, the *RVM provider* and the *Grocery store*. The main objectives of both the stakeholders are naturally maximizing their operating income, but for the grocery store, especially related to RVMs, also maximizing the uptime of the RVM; the reason for this is that the RVM and especially its down time has a noticeable effect to the customer satisfaction of the whole store.

As the red highlight arrow in Figure 10 shows, propagating the objectives of the stakeholders related to the system variables, it is possible to identify contradicting objectives between the two stakeholders. Here, the two stakeholders have conflicting objectives related to the variables *maintenance frequency* and *fault frequency*. On one hand, the primary objective of the grocery store is high uptime, which directly leads to propagated objectives *minimized maintenance* and *fault frequencies*. On the other, after the initial sales of the RVM, the revenue of the RVM provider is dependent only on the amount of maintenance and repair work, done to the machine, leading to the propagated objective of increasing the maintenance frequency. Hence, the propagated objectives of the two stakeholders contradict one another.

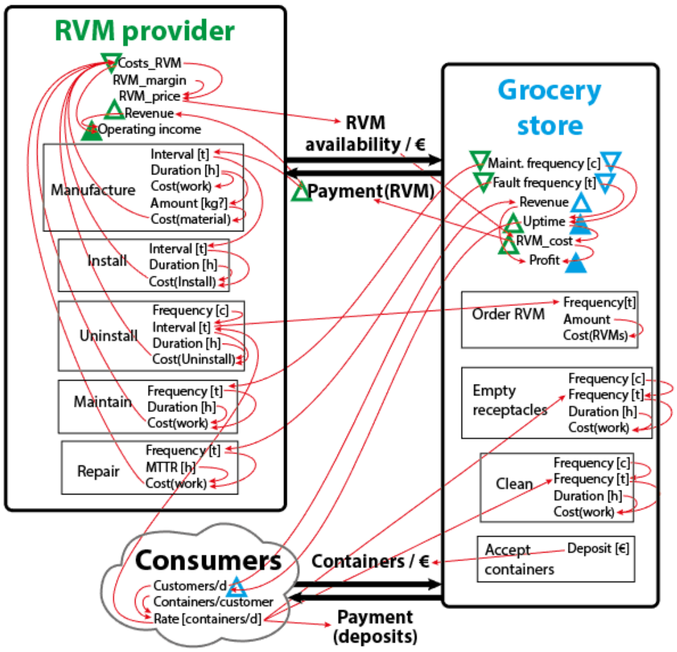

Figure 11 The model subset showing the solution proposed in the RVM design process for removing the identified contradiction; similar notation is used for the objectives as in Figure 10.

Figure 11 shows one of the generic solution principles applied to the RVM case for removing the identified contradiction. For redesigning the causal links in the graph and for aligning the objectives of the two stakeholders, one possibility is to propose a change on the type of value offered by the RVM provider to its customer; instead of selling the machine first and the maintenance service as an add-on, the RVM provider could rather sell the output, use, or availability of the machine e.g. on a monthly fee to the grocery store. This solution emerged during the design process based on business model iterations and discussions with the customer. The method proposed here can be used to study the solution in greater detail; the solution has impacts to the variables in the system, and especially to the revenue logic of the RVM provider, which seems to remove the contradiction between the stakeholders. Thus, by trying to redesign the causal links in the network, and by changing into a service-based earnings logic it seems possible in this case in fact to align the objectives of the two stakeholders.

DISCUSSION

In the case of the RVM case study, the business model can be redesigned to align the objectives of the grocery store and RVM provider. In the case study above using the DACM machinery, it has been visible that a combination of redesign of the network of relationships, moving from the selling of a RVM machine to providing availability to grocery store was a way to align the objectives of the stores and providers. In practice, the outcome here was a result-oriented PSS. The risk of failure is transferred from the customer to the service provider, since they have the tools for lowering the risk through design – the business model just has to support this, to make it economically viable. In this case, the customer would pay for a given, guaranteed level of uptime. Here, as Tukker (Tukker, 2013) states, all the consumables used for delivering the outcome become a cost factor for the service provider, which changes the incentive structure of the business in comparison to traditional product sales, rewarding the service provider for continuous improvement of the system. Nevertheless, it remains that the incentives to move toward those changes are implying more strategic decisions or actions. What can be those incentives is also something that requires analysis. In an RVM market close to monopoly it is difficult to disturb the strategy of a dominant player for smaller companies without the support of grocery stores. Getting the support of grocery stores is then fundamental. For instance by using the *5 why's* approach, popularized by the Japanese industry, it is possible to visualize the strategic level and to find strategies to disrupt the dominant position of few players in this market. Another elements that might help disrupting the current model is the integration of another system in this model, the recycling companies.

CONCLUSION

Designing offerings that combine new physical products and novel business models would be facilitated by a structured modeling framework that allows including both technical and economic elements. This article presents a step towards this by complementing the DACM framework via extending the scope of the framework to include also economic elements, and introducing grafcet-based logic modeling and the use of contradictions as a design aid. The approach is presented through applying it to a reverse vending machine case study for modeling the value network surrounding the reverse vending machine, and the interactions between the central stakeholders. The case study shows that the approach can be used to identify contradictions in the model, and that potential solutions can be found through redesigning the system and the causal interrelationships among the system variables. And although still work in progress, further developing the structured DACM approach would facilitate at least partly automating design processes similar to the case study.

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