Journal of Manufacturing Systems 36 (2015) 203–215

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

Technical Paper

Function and process modeling for integrated product and manufacturing system platforms

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ARTICLE INFO

Article history:
Received 16 May 2013
Received in revised form 17 June 2014
Accepted 18 June 2014
Available online 15 July 2014

Keywords:
Platform development
Functional modeling
Axiomatic Design
Theory of Domains
Function-Means Modeling
Domain mapping

ABSTRACT

Manufacturing companies face increasingly tougher individual customer requirements that force them to revise conceptual solutions for the redesigning of products. This situation limits the reuse of ready-made components and requires physical changes to the manufacturing system. In these settings, platforms must be prepared with greater flexibility to allow development over time. The corresponding platform models need to include conceptual considerations for products and manufacturing systems. The literature advocates functional modeling to capture these considerations but applies it separately to either the product domain or to the manufacturing domain. Further, its relationship to manufacturing processes is not expounded. Thus, functional modeling falls short of its potential to facilitate the integrated development of products and manufacturing systems.

This paper puts forth an integrated platform model using functional modeling to capture the conceptual considerations for products and manufacturing systems together with the manufacturing processes. The model is tested for consistency and then illustrated by studying a real case example from the automotive industry modeled according to the approach suggested. The example shows that the model facilitates an understanding of the design of products and their manufacturing systems, including functions shared across domains and across lifecycle phases. Thus, the model is proposed for the conceptual phase of designing, aimed at reusing and redesigning components, machinery, manufacturing processes and design solutions.

1. Introduction

Companies in the manufacturing industry are faced with numerous challenges related to change and variation. These challenges include [1]:

- Increasing frequency in the introduction of new products
- Changing in parts of existing products
- Large fluctuations in product demand and mix
- Changes in government regulations (safety and environment)
- Changes in process technology

While facing these challenges, companies must continue to strive for more efficiency, product variety and customization. As shown for example by the car industry, this goal can be achieved by developing different car models on the same underbody design and by assembling pre-designed parts to customer order. For other manufactured products, this platform-based development is useful to achieve the combined efficient reuse across variants [2]. In these cases, a platform can be defined as a “set of subsystems and interfaces developed to form a common structure from which a stream of derivative products can be efficiently developed and produced” [3, p. xii].

The success of a platform depends on a company’s ability to maintain stable interfaces over time until a new platform has been developed. Moreover, such platforms and their emerging product variety must be sustained by efficient manufacturing systems, i.e., the physical technical systems that carry out the production of the products, including the factory, facilities, workstations, machines, tools, and operators.

However, there exist factors that prevent static interfaces or, alternatively, shorten the lifetime of a platform, thus limiting the applicability of these conventional platforms. For example, the increasing frequency in the introduction of new products accumulates incremental changes to the products and manufacturing

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http://dx.doi.org/10.1016/j.jmsy.2014.06.012
0278-6125/

systems that ultimately exceed the scope of the platform. Likewise, extensive redesigning from one customer to the next due to tough individual customer requirements limits the reuse of ready-made components and requires physical changes to the manufacturing system, as for instance reported for a supplier in the aerospace industry [4]. In such settings, platforms must be prepared with greater flexibility to allow development over time [5].

The platform contents must be captured in models that encompass earlier conceptual considerations for products and manufacturing systems, representing the output of the conceptual design phases. From a product-centered perspective, this phase is defined as elaborating solutions "by identifying the essential problems through abstraction, by the establishment of function structures and by the search for appropriate working principles and their combination" [6, p. 57]. Seen from the manufacturing perspective, this phase concerns the "determination of manufacturing operations, selection or initial design of machines to provide the required operations, determination of the type of manufacturing systems and identification of possible material handling systems" [7, p. 300].

Conceptual considerations thus include decompositions of functional requirements and solutions to these requirements. Together they express the design rationale, which can be defined as the information about why an artifact is designed the way it is [8]. Moreover, conceptual considerations involve manufacturing processes that link products with manufacturing systems [9,10]. Manufacturing processes include a series of process steps that through the transformation of raw materials and unfinished components leads to the realization of a product. Hereafter these steps are referred to as manufacturing operations, or simply operations.

Finally, the partial reuse of existing components and machinery must be evaluated on the basis of how they relate to overall functionality and performance. For this purpose, their architecture must be understood. This will be defined as the scheme by which the functions of a system are allocated to physical components (as an adaptation of the definition of *product architecture* by Ulrich [11]).

Manufactured products and the manufacturing systems that produce them are multi-technological systems that consist of different types of hardware subsystems (e.g., mechanic, hydraulic and electronic hardware) and software subsystems. These systems and their subsystems interact with each other and with the surrounding environment [12] during the different phases of their lifecycles in so-called lifecycle meetings [13]. In particular, the interactions between the product and the manufacturing system during the manufacture of a product must be understood and managed during and after the conceptual design phases because these interactions govern how the product and manufacturing system mutually affect each other. A change in a product may require new tools for its manufacture or a product may require modification to allow the implementation of a more efficient manufacturing sequence.

In general, a platform model to support product development over time must be a sufficiently information-rich and adaptable source of knowledge to enable the effective and efficient generation of quality assured variants. The products and manufacturing systems of the platform must be developed to a level of maturity and expressed by means of an artifact model that allows for reuse or redesign [5]:

- to develop new platform systems aimed at original or updated settings
- to extend original or previously required functionality and performance
- for the ordered configuration of quality assured variants within platform limits.

This paper focuses on development related to the first two points. Thus, it aims to support platform-based development in settings that require redesigning and revisiting of conceptual considerations rather than being limited to the reuse of ready-designed components. To achieve this objective, it examines the possibility of integrating product and manufacturing system descriptions into one integrated platform model. Specifically, it focuses on supporting these conceptual considerations rather than providing comprehensive solutions that include and extend to detailed designing of the product and manufacturing system and detailed manufacturing process planning.

2. State of the art

The literature addresses the designing of products and manufacturing systems from two different perspectives. The first perspective regards both as artifacts designed for the generic purpose of transforming inputs into outputs [14]. The second perspective acknowledges both their differences and inherent relationship; typically, only one manufacturing system is built to manufacture many individual products. Both perspectives are reflected, specifically elaborating on the methods aimed at supporting conceptual design processes of products and manufacturing systems.

2.1. Modeling functions and solutions

The representation of the design rationale of a system and its functional decomposition is addressed by various methods. One of these methods, Function-Means Modeling, captures the designs of technical systems and their rationale to create a decomposition of functions by alternating the means used to solve these functions [15,16]. It distinguishes between functional requirements (FR) that are solved by various means and non-functional constraints (C) that limit the means selected [17]. Each means accomplishes a single function, whereas several constraints can limit its selection. As carriers of functionality, means are also known as organs [14] or design solutions (DS) [5]. By adding alternative means and supplementary design information, Function-Means models are enhanced and refined [18]. Fig. 1 schematically illustrates a Function-Means tree involving modeling elements as different relationship types. However, manufacturing processes are not addressed through Function-Means Modeling.

In contrast to this, Axiomatic Design connects the product design to manufacturing processes by using so-called process variables [19]. Expansions achieve an objective-solution mapping for the product and its manufacturing process separately [20,21] without explaining the manufacturing system in functional terms. Other adaptations of Axiomatic Design consider the functional decomposition of a manufacturing system [22,23] without extending it to product design.

Neither Function-Means Modeling nor Axiomatic Design address how the functions of the products or functions of the manufacturing system are mapped or linked to existing product components and existing machinery, i.e., the architecture. The means, design parameters and process variables express this information indirectly without explicitly including existing product components and machinery.

2.2. Design solutions and parts

Connecting existing product components and machinery to conceptual solutions leads to causal relationships between the modeling elements. Whereas a single design solution accomplishes